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Comparison of two methods to estimate the structure-borne sound by installations in buildings

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Abstract

Vibrating sources in buildings, such as service equipment, elevators and electric devices, often cause a lot of noise because of the mechanical excitation of building elements (structure-borne sound). De draft standard prEN 12354-5 describes how the normalized sound pressure in a room can be calculated based on the injected structure-borne sound power of an installation in another room. Estimating this power is not simple, because both source properties (installation) as receiver properties (building element) play a role. The draft standard prEN 15657-1 delivers a method to do this for sources of which the mobility is much larger than the mobility of the receiving building element, therefore making a measurement of the source mobility unnecessary. In this method, the source is put into operation on a plate that is resiliently connected to the surroundings. The injected power in this so-called “reception plate” is then determined out of the structure-borne sound power in the diffuse velocity field of the plate. In this investigation, the injected structure-borne sound power by an operating fitness vibration plate into three different floors between two acoustical transmission rooms is determined via the reception plate method. The power is also calculated according to the more exact “mobility method”, that takes the source mobility into account. Finally, the results of both methods are compared to each other.

1. Introduction

Installation noise is a familiar phenomenon in buildings. An operating installation causes its supporting structure to vibrate. These vibrations spread over the entire building, resulting in a sound field in every room (see Figure 1). The draft standard prEN 12354-5 describes how the normalized sound pressure level L_n can be determined in a room of a building, based on the injected structure-borne sound power $L_{Ws,inst}$ of the installation in element i of the source room [1]:

$$L_{n,s,ij} = L_{Ws,inst,i} - D_{sa,i} - R_{ij,ref} - 10\lg\frac{S_i}{S_{ref}} - 10\lg\frac{A_{ref}}{4} \qquad (1)$$

In this equation j is the radiating element in the receiver room, D_{sa} is a correction term to go from structure-borne to airborne sound, $R_{ij,ref}$ is the flanking sound reduction term between element i in the source room and element j in the receiver room, S_i and S_{ref} are the surfaces of element i and the reference surface (10 m²) and A_{ref} is the reference absorption area.

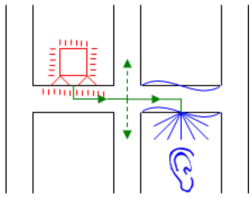

Figure 1: An operating installation injects structure-borne sound power into the structure (red part), after which this power is distributed over the entire building (green part). Finally the vibrating structure leads to a sound field in any room of the building (blue part).

1.1 Mobility method

Especially the power transfer from source to structure $L_{W,inst,i}$ is difficult to determine (the red part in Figure 1). Both the mobility of the source $\underline{Y}_S$ as the mobility of the receiver at the contact points $\underline{Y}_R$ influence the power injection[1]. This is visible in the so-called “mobility method”, which should be an exact formulation of the complex energy between a source and a receiver. For a 1D- and 1 contact point situation, this energy can be written as follows [2]:

$$\underline{W} = \frac{1}{2} \frac{\underline{Y}_R}{\left|\underline{Y}_S + \underline{Y}_R\right|^2} \left|\underline{v}_{Sf}\right|^2 \qquad (2)$$

where an underscore ‘_’ denotes a complex quantity.

In this equation $\underline{v}_{Sf}$ is the “free velocity” at the contact point of the source. This is the velocity that is measured when the source is operating without fixing nor supporting. This situation can be achieved by placing the source on a resilient layer so that the mass-spring resonance frequency of this construction – the source being the mass and the layer being the spring – is at least three times lower than the lowest frequency of interest [3].

The main advantage of the mobility method is that it is a theoretical exact method. Upon that, it is also a true prediction method, which can be important for machine developers (at the source’s side) and for building element constructors and contractors (at the receiver’s side). One can know a priori what the injected power W will be[2] before the source is connected to the receiver.

However, there is a major drawback of this method. When a source has multiple contact points (like in almost every real-life case), equation (2) extends to a matrix formulation, where the mobilities become matrices with the point mobilities on their diagonals and transfer mobilities elsewhere[3]. When also other degrees of freedom are considered, even other mobilities show up. It is a lot of work to determine all these mobilities, not only at the source’s contact points, but also on the receiver at the location of the contact points.

1.2 Reception plate method

Another method has been developed in the previous years, which lowers the amount of necessary measurements greatly. Moreover, it is also a prediction method and it delivers a lot of insight because of its simplicity. This method is called the “reception plate method” and is being standardized in part 1 of prEN 15657 [4]. The method makes use of the energy balance between the injected structure-borne power in a resiliently mounted plate and the dissipated power of this plate, that can be determined by measuring the averaged squared translational

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[1] The (mechanic) mobility of an object is its ability to move at a certain velocity when a certain force is applied to it. In formula: $\underline{Y} = \underline{v} / \underline{F}$.

[2] The injected power or the power flow W is the real part of the complex power $\underline{W}$.

[3] Point mobility is the mobility when the velocity is taken at the same point as the point of the force excitation. Transfer mobility is the mobility when the velocity is taken elsewhere.

velocity <$v^2_{x,t}$> in the diffuse field of the plate. For a source with only 1 contact point, the injected power $W_{s,rec}$ becomes:

$$W_{s,rec} = \eta_{rec} 2\pi f m_{rec} S_{rec} \left\langle v_{x,t}^2 \right\rangle \quad (3)$$

with η_{rec} the loss factor of the plate, m_{rec} the surface mass and S_{rec} the surface.

Thereafter, the ratio of the mobility of the building element under study $\underline{Y}_i$ with the mobility of this reception plate $\underline{Y}_{rec}$ can be used to predict the structure-borne power $W_{inst,i}$ that would be injected in the building element:

$$W_{inst,i} = W_{s,rec} \frac{\mathrm{Re}\{\underline{Y}_i\}}{\mathrm{Re}\{\underline{Y}_{rec}\}} \quad (4)$$

When the source with multiple contact points, the mobilities in equation (4) can be replaced by the average of the so-called “effective mobilities” $\underline{Y}^{\Sigma}{}_k$. The effective mobility of point k takes all mobilities related to that point (point and transfer mobilities) together [5]:

$$\underline{Y}_k^{\Sigma} = \underline{Y}_k + \Sigma \frac{\underline{F}_l}{\underline{F}_k} \underline{Y}_{k,l} \quad (5)$$

Because the forces $\underline{F}$ are generally unknown, assumptions have to be made. The first assumption is that the amplitude of the forces in the different contact points k, l are equal. Concerning the phase differences between the forces, one can assume there is zero phase difference or there is a random phase difference. Zero phase differences will more likely occur at lower frequencies, while random phase differences are a more acceptable assumption for higher frequencies.

The main advantage of the reception plate method is that it is straightforward. It is also possible to quickly compare different sources with each other.

The major drawback of the method is that it is only applicable on sources of which the mobility is much higher than the mobility of the receiving building element (and of the mobility of the reception plate itself), so-called “force sources”. This means it is mostly applicable for rather light sources on heavy building elements. Part 2 of the standard EN 15657 will focus on how to handle sources with a mobility much lower than the mobility of the building elements (heavy sources on lightweight floors).

2. Source and receivers

2.1 Source: fitness vibration plate

As a vibrating source, a fitness vibration plate is used (see Figure 2(a)). The platform on this device can vibrate vertically at an amplitude of 1.5 mm or 3 mm and at frequencies between 20 Hz and 60 Hz, in steps of 1 Hz. The vibrating platform is separated from a bottom plate via 6 vibration isolators. The machine has three contact points with the receiving structure, also consisting of vibration isolators, denoted *a, b* and *c* (see Figure 2(b)). Since contact points *b* and *c* are geometrically symmetrical, analogous behaviour of these points can be expected.

The operating mechanism consists of two electric motors with unbalances, so that the vibrating plate is lifted once at each turn by forces of inertia. Since the two motors operate in counter-phase, only vertical vibrations are produced (in theory). The operating machine is known to invoke a lot of acoustic annoyance in rooms in the neighbourhood of the source room.

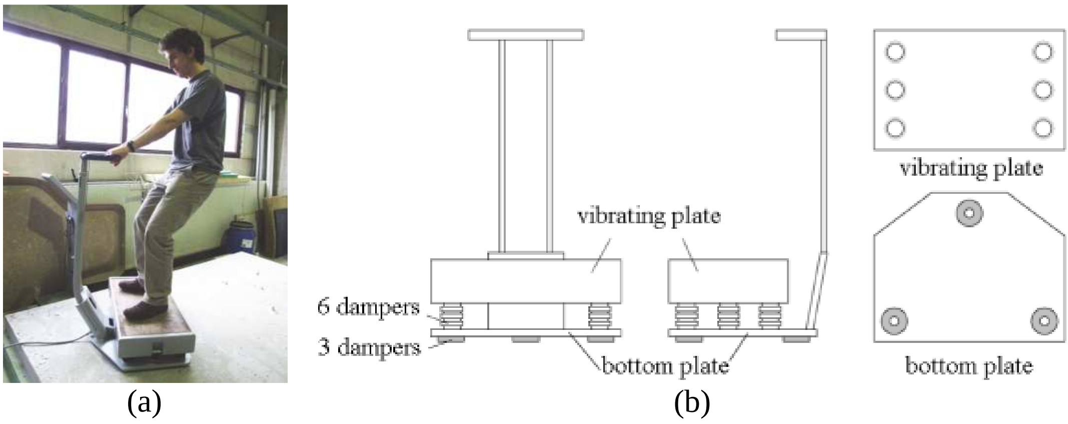


Figure 2: (a) Fitness vibration plate with a person training on it and (b) different schematic views of the plate

2.2 Receivers

2.2.1 Reception plate

The reception plate is a reinforced concrete plate of 2,0 x 2,8 m² and 10 cm of thickness that is mounted resiliently (see Figure 3). Therefore, this reception plate, located at the acoustical laboratory of the Belgian Building Research Institute, complies with the requirements outlined in prEN 15657-1 [4]. In Figure 3, also the use of the reception plate is shown: the fitness vibration plate is put into operation on the reception plate while accelerometers measure the velocity (integrated acceleration) in the diffuse field of the plate.

Figure 3: Construction and use of the reception plate

2.2.2 Lightweight floor

The lightweight floor in the experiments is a wooden joist floor of 3,0 x 3,0 m² (see Figure 4 and Table 1). This floor is mounted in the opening between two acoustical transmission rooms in the laboratory for acoustics of the K.U.Leuven. The floor is simply supported on a concrete console.

Figure 4: Construction of the wooden floor

layer	thickness (cm)
fibreboard	1,8
7 joists (Ø 19 x 7 cm²)	19
glass wool	6
aluminium profiles	2,7
2 gypsum board plates	2 x 1,25

Table 1: Properties of the wooden floor

2.2.3 Heavy-weight floor

The heavy-weight floor is a concrete floor of 2,19 x 2,19 m² which is mounted separately in the opening between two transmission rooms via 8 bolts (see Figure 5 and Table 2**).**

Figure 5: Concrete floor with the fitness vibration plate on top of it

layer	thickness (cm)	Young's modulus (GPa)	density (kg/m³)
epoxy floor	0,3	8,4	1800
epoxy mortar	2,5	7,5	2000
concrete	7,4	30	2300

Table 2: Properties of the concrete floor

2.2.4 Floating floor

The floating floor consists of the concrete floor as a base, a layer of mineral wool and a layer of lightweight concrete of 1,5 x 1,5 m² (see Figure 6 and Table 3). Because the mineral wool and the lightweight concrete don't touch the surroundings, the floating floor has the same boundary conditions as the concrete floor.

Figure 6: Floating floor with the fitness vibration plate on top of it

layer	thickness (cm)	Young's modulus (GPa)	density (kg/m³)
lightweight concrete	5	1,5	1800
mineral wool	3	0,0003	100
epoxy floor	0,3	8,4	1800
epoxy mortar	2,5	7,5	2000
concrete	7,4	30	2300

Table 3: Properties of the floating floor

3. Mobility method

As mentioned in equation (2), three quantities need to be measured to calculate the injected structure-borne sound power by a source in a receiver: the free velocity $\underline{v}_{Sf}$, the source mobility $\underline{Y}_S$ and the receiver mobility $\underline{Y}_R$.

To determine the free velocity and the source mobility, the source has to be part of a mass-spring-system (the source being the mass) of which the resonance frequency is at least three times as low as the lowest frequency of interest [3]. Since the source is the fitness vibration plate, which can operate down to 20 Hz, the lowest frequency of interest could be 12 Hz. Therefore, the resonance frequency of the mass-spring-system to be constructed, needs to be 4 Hz or lower.

A simple thick soft layer with the source on top of it appears to be insufficient for this purpose, because the resonance frequency is about 7 Hz. Another solution, with the fitness vibration plate hung from two inner tires for bicycles, has a resonance frequency of approximately 4 Hz. Therefore, the free velocity and the source mobility are measured at the contact points in this situation (see Figure 7). As visible in the figure, the mobility is measured with an impact hammer.

Figure 7: The fitness vibration plate hung from two inner tires for bicycles makes the measurement possible of the free velocity and the source mobility.

The measurement result of the free velocity $\underline{v}_{Sf}$ while the fitness vibration plate is operating at a frequency of 40 Hz is shown in Figure 8. Both the spectral measurement result as the third-octave result is shown. The distinct peak at the operating frequency is clearly visible. Also noticeable are the peaks at the harmonics, especially in the frequency range between 125 and 500 Hz. These peaks will play an important role in the calculated power by equation (2).

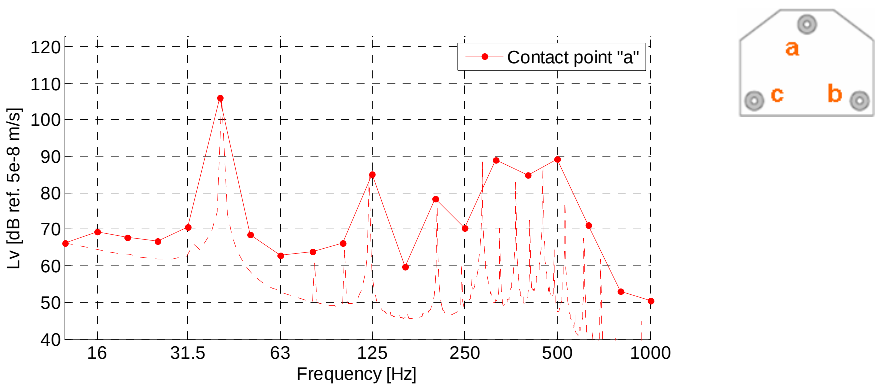


Figure 8: Free velocity of contact point *a* while the fitness vibration plate is operating at a frequency of 40 Hz. Both the spectral as the third-octave result is shown.

The measurement results of the magnitude of both the source mobility and the receiver mobilities are shown in Figure 9. The receiver mobilities are also measured by use of an impact hammer. It is visible that the mobilities of the reception plate (blue line) and the concrete floor (green line) are the lowest and that they are of equal magnitude. This is logical, since they consist of the same material and have about the same (equivalent) thickness. Therefore, their mobility heads towards a constant mobility at the higher frequencies, which is the mobility of an infinite concrete slab of about 10 cm thickness (the so-called "characteristic mobility").

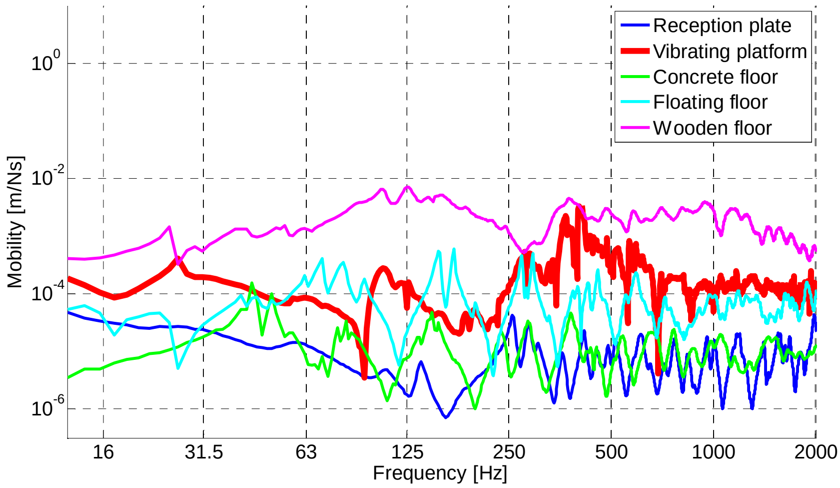


Figure 9: Magnitudes of the source mobility $\underline{Y}_S$ and receiver mobilities $\underline{Y}_R$ in contact point *a* by use of the impact hammer measurement method

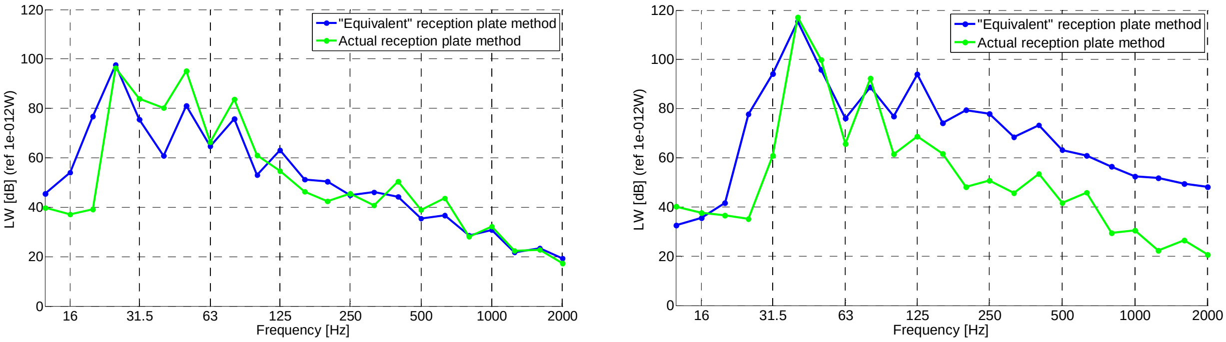
A difference between the concrete floor mobility and the reception plate mobility though is that there is a higher mobility of the concrete floor at about 44 Hz, which is the first bending mode resonance frequency of that floor. The peak is rather distinct because of the low loss factor, which was confirmed experimentally but is not shown in this paper. The shape of the reception plate mobility is rather smooth because of the higher loss factor.

Further, one can see that the mobility of the source (the vibrating platform, red line) is higher than the mobility of the reception plate and of the concrete floor, except at the first bending mode resonance frequency of the concrete floor (44 Hz), where the red and green lines match. A resonance is to be expected when the source is operating on the concrete floor at a frequency of around 44 Hz, which was also confirmed experimentally.

Since the mobilities of the floating floor (light blue line) and the wooden floor (purple line) are larger than the source mobility (red line), the force source assumption is not valid when the source is placed on one of these floors. Therefore, the reception plate method cannot be applied to determine the injected structure-borne sound power in these cases, which was also confirmed by the analyses. For this reason, the floating floor and the wooden floor are not considered further, since comparison between measurements and experimental predictions by the mobility method is aimless a priori.

4. Reception plate method

As an approximation, an energy balance can be applied to the relatively separated concrete floor in the lab, supposing that all delivered energy is dissipated by this “equivalent” reception plate. The injected power calculated by this “equivalent” reception plate method, where the floor is considered as a reception plate (equation (3)), is compared with the actual reception plate method with the mobility ratio correction (equations (3) and (4)) in Figure 10 for the case in which the fitness vibration plate is operating at frequencies of 24 Hz and 40 Hz.



Operating frequency: 24 Hz Operating frequency: 40 Hz

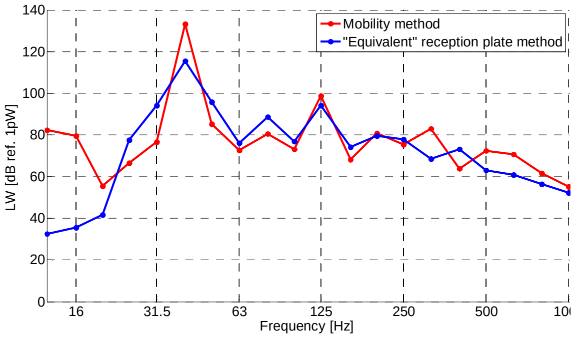
Figure 10: Comparison between the calculated injected power by the vibration plate in the concrete floor when the floor is considered as a reception plate (“equivalent” reception plate method, blue line) with the calculation when the actual reception plate method with the mobility ratio correction is used (green line) for an operating frequency of 24 Hz (left) and an operating frequency of 40 Hz (right)

Apart from low-frequency deviations because of a poor floor/plate modal density at these frequencies, the comparison between the two experimentally predicted powers is rather good for an operating frequency of the source of 24 Hz. The large discrepancy at 40 Hz is due to invalidity of the force source assumption of the source on the concrete floor as their mobilities are matching at around 44 Hz (see Figure 9). It is clear that the reception plate method cannot be used when the force source assumption is invalid.

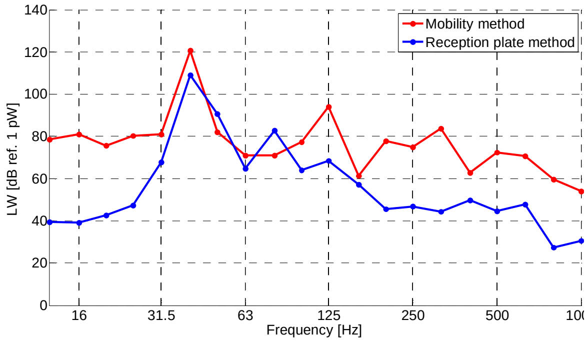
For the operating frequency of 40 Hz, a large difference between the two experimentally predicted powers is visible. This is because the mobility matching at around 44 Hz leads to a huge resonance phenomenon when the operating frequency is 40 Hz. Apparently this resonance phenomenon makes power predictions with the reception plate method **impossible for all frequencies**, especially in the higher frequency range, and not only on the frequency band of 40 Hz.

5. Comparison of two methods

In Figure 11, a comparison between the calculated injected power via the two methods is shown for the case in which the fitness vibration plate is operating at 40 Hz on the concrete floor and for the case in which it is operating under the same conditions on the reception plate. Notice that for the reception plate method in this figure, the receiver itself is considered as a reception plate (“equivalent” reception plate method). There is a good correspondence between the calculated injected powers in the case with the concrete floor, but the mobility method seems to overestimate the power via the reception plate method in the case with the reception plate, especially for the frequencies from 125 Hz and higher.



Source on concrete floor



Source on reception plate

Figure 11: Comparison between the calculated injected power by the mobility method (red line) with the calculated power by the "equivalent" reception plate method (blue line) when the vibration plate is operating at 40 Hz on the concrete floor (left) and on the reception plate (right). For the case of the reception plate, the "equivalent" reception plate method is the same as the actual reception plate method.

When looking back at the shape of the free velocity in Figure 8, there is a great similarity with the shape of the calculated injected power via the mobility method in Figure 11 (red line), as expected. This means that the free velocity harmonics of the operating frequency penetrate into the injected power of the vibration plate into a receiver (see equation (2)) and that they largely dominate the power's shape. This shape seems to lead to a fine resemblance with the power calculated via the "equivalent" reception plate method – which is considered here to deliver the exact injected power – but ***only*** when source and receiver mobility match and thus a resonance phenomenon occurs (left in Figure 11). In the other case, the shape of the power calculated via the mobility method is not reflected in the shape of the 'exact' injected power because the free velocity harmonics seem to have disappeared (right in Figure 11).

A summary of the findings is shown in Table 4. Theoretically, the mobility method should be fine independently of the force source assumption. This can only be due to three quantities, namely the free velocity, the source mobility or the receiver mobility (see equation (2)). The receiver mobility is thought to be correct since it is also used in the reception plate method and because this method seems to be working fine.

Mobility ratio	**Resonance**	**Rec. plate meth.**	**Mobility meth.**
$\lvert\underline{Y}_S\rvert \gg \lvert\underline{Y}_R\rvert$ for all f	⊘	✓	⊘
$\lvert\underline{Y}_S\rvert \gg \lvert\underline{Y}_R\rvert$ but $\lvert\underline{Y}_S(f_x)\rvert \approx \lvert\underline{Y}_R(f_x)\rvert$ (*)	⊘	✓ (but not at f_x)	⊘
$\lvert\underline{Y}_S\rvert \gg \lvert\underline{Y}_R\rvert$ but $\lvert\underline{Y}_S(f_{oper.})\rvert \approx \lvert\underline{Y}_R(f_{oper.})\rvert$	✓	⊘ **(for all f !!)**	✓
$\lvert\underline{Y}_S\rvert \approx \lvert\underline{Y}_R\rvert$	✓	⊘	✓
$\lvert\underline{Y}_S\rvert \ll \lvert\underline{Y}_R\rvert$	⊘	⊘	?

(*) $f_x \neq f_{oper.}$

Table 4: Validity of the two considered power prediction methods in function of the mobility ratio at different frequencies with the fitness vibration plate as the source and with the free velocity and source mobility measured when the vibration plate is operating freely

However, it is possible that the free velocity cannot be measured when the source is really 'free' because the internal mechanisms of the source could behave differently than when it the source 'feels' the resistance of a receiver. This could explain the disappearance of the harmonics of the free velocity when the receiver mobility is low. A solution could be that the free velocity is determined out of indirect measurements.

Also, it is possible that the source mobility is dependent on static loads. This means that the mobility, measured when the source is hung freely, will be different than a mobility that would have been calculated out of indirect measurements where the source is put on a receiver. Therefore, an indirect measurement of the source mobility should be performed to verify this.

Conclusions

The reception plate method gives a good approximation of the injected structure-borne sound power by the fitness vibration plate in a receiving building element in the frequency ranges where the source mobility is higher than the receiver mobility, i.e. where the force source assumption is valid. As expected, the method fails in frequency ranges where the source mobility matches the receiver mobility because of an invalid force source assumption. But when the operating frequency of the source lies in a frequency range with matching source and receiver mobility, a huge **resonance** occurs and experimental predictions seem to **fail for all frequencies**, especially for the higher frequencies.

The mobility method should theoretically be correct independent of the force source assumption. However, with the fitness vibration plate as a source and direct measurements of free velocity and source mobility, the method seems to **fail when the force source assumption is valid**. Ironically with respect to the reception plate method, the mobility method delivers good experimental predictions when there is a huge resonance of the source-receiver system, i.e. when the source behaves almost like when it is operating freely. Therefore, it is thought that the free velocity cannot be measured directly in cases with a valid force source assumption, since the source must be operating differently when standing on a low mobility receiver. Also, the source mobility should be measured indirectly in these cases, because it is possible that it is dependent on static loads that are not present in the case where the source is operating freely.

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